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THE MICROWAVE APPLICATIONS THEORY PROGRAM AT NRL AND SOME CHEMI--ETC(U)

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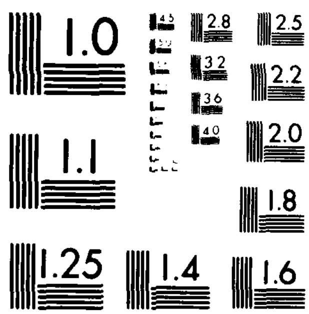

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A brief outline of the Microwave Applications program at NRL is presented. The goal of the program is to develop comprehensive codes for microwave air breakdown and microwave interaction with matter which can easily be applied for a wide range of applications.

Also presented are results of microwave energy deposition in the ionosphere using the NRL Master Code for the disturbed E and F regions. Time histories of oxygen metastable states are presented for several levels of microwave power. From these, emission at 5577 Å and 6300 Å can be obtained.

CONTENTS

THE MICROWAVE APPLICATIONS THEORY PROGRAM AT NRL AND SOME CHEMISTRY CODE APPLICATIONS TO IONOSPHERIC HEATING BY MICROWAVE RADIATION

1. INTRODUCTION

The advent of high power pulsed microwave devices, the magnetrons, at NRL,[1] which currently generate $\sim$ 1 G Watt at $\lambda \simeq 10$ cm and a pulse duration of $\sim$ 30 nsec, provide a new opportunity for research in various areas of microwave applications.

Two areas of interest in the high power microwave applications are: the microwave interaction with air (air breakdown) and the microwave interaction with matter (conductors and dielectrics). These two areas have potential applications of considerable value, however, they do require,[2] in general, a large amount of power. The advent of the magnetron and the free electron lasers and their future developments could provide the necessary power using fewer devices compared to the old ones with power levels of 10^6 watts or less. However, in order to delineate and advance various applications of high power microwave devices, a concerted effort in the areas of air breakdown and interaction with matter is desired. Especially since none of the above applications have been carried out for microwave powers above 10^6 watts. To this end the high power microwave applications research at NRL is conducted at two fronts; experimentally and theoretically. The theoretical aspect of the program and its goals are described in this report. Furthermore, the report presents calculations for threshold power of air breakdown and its dependence on the microwave frequency, pulse duration and the ambient pressure. In addition, some calculations are given for the heating of the ionosphere and the subsequent emission of the heated region.

Manuscript submitted June 16, 1980.

2. THE MICROWAVE THEORY PROGRAM AND ITS GOALS

The theoretical program can best be described as a basic research with applications overtone. It is divided into two categories, the atmospheric breakdown and the interaction with matter.

2.1 THE ATMOSPHERIC BREAKDOWN

To transmit and/or to focus pulsed microwave radiation from the ground to any point in space, the radiation must propagate through the atmosphere. The attenuation of the microwave radiation, as it propagates through air, depends on various parameters, among these are: the atmospheric conditions (air density, temperatures), the radiation frequency, the power density, the pulse width, etc. At power levels near threshold for air breakdown, the radiation will be blocked from reaching its destination due to air breakdown. Therefore, it is essential that we understand fully the breakdown phenomena and its dependence on all those parameters. However, the understanding of the breakdown to generate a disturbed atmospheric condition may facilitate the utility of air breakdown for certain useful applications. A disturbed air generated by microwave breakdown will emit radiation from uv to ir which may have some impact on sensors and detectors. The generated plasma, depending on its size and duration, may also affect communications.

Therefore, the goal of the theoretical program, in this area, is to develop a theoretical model (a computer code) which describes the phenomena of the radiation absorption, the subsequent avalanche ionization, the heating and dissociation of air molecules, the generation of shocks, overpressures, the emission of the disturbed air and its subsequent relaxation. The model should incorporate hydrodynamics and a detailed air chemistry into a code to describe the phenomena satisfactorily for all altitudes and microwave frequencies.

The generated code, will be utilized to predict

(a) the dependence of air breakdown on microwave power density, the microwave frequency, atmospheric pressure (altitude), the radiation pulse width and the pulse shape.

(b) the dependence of breakdown on two incident frequencies, two microwave or one microwave and an optical frequency. The impact of two stage ionization and multiphoton ionization.

(c) shocks, overpressures and their dependence on the incident microwave power density, ambient pressure, radiation pulse shape and width.

(d) spatial and time dependence of the air species, degree of ionization, dissociation, electron, ion and cluster ion densities (depending on altitudes, etc.) and various kinetic temperatures e.g. the electron temperature, the vibrational temperature and the neutral temperature.

(e) emission from the disturbed air (uv, visible ir, etc.). Its magnitude, duration and its dependence on microwave power density, frequency, pulse width, pulse shape and the altitude.

(f) plasma absorption length, power per unit volume expended for breakdown to generalize towards larger volumes. Power, number of pulses and their time separation needed to sustain such a plasma.

(g) relaxation of the disturbed air and the impact of the late time air chemistry on multi pulse breakdown characteristics.

Another interesting aspect is the air breakdown and its characteristics near surfaces. This phenomenon will also be studied and provides a link to the interaction of radiation with matter.

2.2 MICROWAVE INTERACTION WITH MATTER

This aspect of the theoretical program concentrates on the interaction of microwave radiation with conductors and dielectrics in vacuum and rarefied atmosphere. Its purpose is to model the physical changes in matter and how they are brought about by the incident radiation? These physical changes are the heating of the target (its temperature), melting and vaporization. And how these changes depend on incident power densities, radiation wavelengths, the pulse width and the pulse shape? The theoretical model which

describes this phenomena entails radiation absorption, heat equation vaporization, breakdown in vaporized region, the hydrodynamics of the vaporized region, energy coupling and decoupling to the solid matter by the vaporized and ionized region. These basic elements are to be incorporated into a computer code which will be utilized to predict:

(a) the temperature of the matter under irradiation, the melting point and the vaporization. The dependence of these changes on the microwave power density, microwave frequency, the duration of the pulse and the shape of the pulse and the angle of incidence.

(b) breakdown of the vaporized atomic species, its hydrodynamic development, degree of ionization and the range of emission.

(c) the effect of the broken down vapor on coupling or decoupling the microwave energy to the solid matter.

(d) the emitted radiation from the vaporized and ionized region and their absorption into the matter.

(e) generated shocks or detonation waves and their impact on the matter.

It is obvious from these brief statements, on the goals of the theoretical program, that large computer codes with detailed ab initio type calculations are needed. However, estimates can be made, using simple theoretical models, to gain an understanding of some or more aspects of the problem.

These approaches will be utilized as one proceeds to develop the detailed computer model which in principle should provide completeness to the solution of the problem.

Simple theoretical models are pursued in the next section to obtain some characteristics of the air breakdown phenomena.

3. AIR BREAKDOWN

In this section a brief theory of the microwave air breakdown is given. Quantitative relations are derived for the breakdown threshold power, its dependence on the microwave wavelength and pulse lengths. Calculations are presented for various altitudes.

3.1 THEORY OF BREAKDOWN

The breakdown in air is exemplified by the generation of a plasma. This occurs when sufficient power from a microwave source is focussed in air, whereupon the free electrons, present, gain energy under the influence of the intense electric field associated with the focussed radiation. The energy gained by electrons is expended in producing more electrons by electron impact ionization, culminating in cascade ionization.

There have been considerable experimental studies of breakdown and ionization rates in many gaseous elements and in air under the influence of microwave radiation.[3-10] With the advent of lasers and high power Q-switched lasers, however, the air and gaseous breakdown studies at optical frequencies have increased considerably.[11,12]

The mechanism for gas breakdown can be explained by the classical microwave breakdown theory.[4] The electron gains energy from the electric field only when it collides with an atom and the sudden change in its velocity results in the transfer of the oscillation energy gained from the field into random motion. This energy gain process has been shown to correspond[13] to the quantum mechanical description of the energy gain by the free electrons from the radiation field through the free-free transitions in the field of an atom.

The equation of motion of a free electron, in air, under the influence of an oscillating electric field is

$$m \frac{d\vec{v}}{dt} = - \nu_m m\vec{v} - eE \exp(-i\omega t) \qquad (1)$$

where ν_m is the collision frequency for momentum transfer, ω is the frequency of the radiation field, E, and v is the velocity of the electron. In Equation (1), the term $\nu_m m\vec{v}$ represents a continous resistive damping force on the electron due to collisions with atoms and molecules. The real part of the velocity, in phase with the oscillating field is

$$v = \frac{e\nu_m \text{Exp}(-i\omega t)}{m(\nu_m^2 + \omega^2)} \qquad (2)$$

The rate of energy gain by the free electron $\left(\int_0^\tau v.E.\ \text{Exp}(-i\omega t)dt\right)$ is

$$\left.\frac{d\varepsilon}{dt}\right)_g = \frac{e^2E^2}{m\nu_m} \frac{\nu_m^2}{\omega^2 + \nu_m^2} = \frac{e^2E_e^2}{m\nu_m} \qquad (3)$$

where $E_e^2 = \frac{E^2 \nu_m^2}{\omega^2 + \nu_m^2}$ is the effective electric field (equivalent to a static field).

On the other hand, the electron loses its energy through elastic and inelastic collisions. Electron energy is also lost by attachment, recombination and diffusion. The total energy lost can be expressed as

$$\left.\frac{d\varepsilon}{dt}\right)_\ell = - \frac{D\,\bar{\varepsilon}}{\Lambda^2} - \frac{2m}{M} \varepsilon\, \nu_m - \left(\nu_i\varepsilon_i + \nu_a\bar{\varepsilon} + \Sigma_e \nu_e \varepsilon_e + \nu_r\, \bar{\varepsilon}\right) \qquad (4)$$

where D is the diffusion coefficient, Λ the diffusion length, $\bar{\varepsilon}$ is the average electron energy, ν_i, ν_a, ν_e and ν_r are the collision frequencies for ionization, attachment, excitations and effective recombinations, respectively, while ε_i and ε_e are the corresponding energies for ionization and excitations,

respectively. The second term on the right hand side of Equation (4) represents the energy loss by electrons through elastic collisions. Therefore, the net energy gained by electrons is

$$\frac{d\varepsilon}{dt} = \left.\frac{d\varepsilon}{dt}\right)_g - \left.\frac{d\varepsilon}{dt}\right)_\ell \tag{5}$$

Furthermore, the time development of the electron density, n_e, can be described by

$$\frac{dn_e}{dt} = n_e\nu_i - n_e\nu_a - n_e\frac{D}{\Lambda^2} - n_e\,\nu_r \tag{6}$$

where it is obvious that electron attachment and, diffusion and recombination will control the cascade ionization, and must be overcome for breakdown to occur. Two limiting cases of Equation (6) can be of great interest. These are the diffusion controlled and attachment controlled cases of air breakdown. At atmospheric pressure, however, the air breakdown is attachment controlled. To estimate the magnitude of the terms in (6), consider the condition for a cw breakdown $\left(\frac{dn_e}{dt} = 0\right)$ which implies that

$$\nu_i = \nu_a + \frac{D}{\Lambda^2} + \nu_r \tag{7}$$

The diffusion coefficient can be expressed as[5]

$$D\,p = 3.2 \times 10^5 \bar{\varepsilon} \tag{8}$$

where p is the pressure in Torrs and $\bar{\varepsilon}$ is the average electron energy in units of eV. Thus for typical energies of few eV and pressure of one atmosphere (760 mm), the diffusion coefficient is $D \simeq 8 \times 10^2$ $(\frac{cm^2}{sec})$. This implies that the rate of diffusion from an area of 1 cm^2 is $\sim 10^3$ sec^{-1} which is very small compared to the attachment rate of electrons to O_2. There are two distinct

attachment processes that an electron undergoes in air. These are: the three-body attachment to O_2 i.e.

$$e + O_2 + O_2 \rightarrow O_2^- + O_2 \qquad (9)$$

$$e + O_2 + N_2 \rightarrow O_2^- + N_2 \qquad (10)$$

and the dissociative attachment

$$e + O_2 \rightarrow O^- + O \qquad (11)$$

The rate coefficients for reactions (9) and (10) are[14] $3.5 \times 10^{-31} \frac{1}{T_e} \mathrm{Exp}(-0.052/T_e)$ and 10^{-31} cm^6/sec, respectively. At room temperature, the attachment rate due to reactions (9) and (10) is $\sim 6 \times 10^7$ sec^{-1} which is larger than the diffusion rate by many orders of magnitude. Reaction (11), however, is highly dependent on the electron energy where the cross section[15] is appreciable for electron energies (4.5-10 eV), the peak of this cross section is 10^{-2} π a_o^2 at electron energy of 6.5 eV.

Recombination in air proceeds through dissociative recombinations

$$N_2^+ + e \rightarrow N + N \qquad (12)$$

$$O_2^+ + e \rightarrow O + O \qquad (13)$$

and by two and three body recombinations. These can be presented by the following relations:

$$A^+ + e \rightarrow A + h\nu \qquad (14)$$

$$A^+ + e + e \rightarrow A + e \qquad (15)$$

$$A^+ + e + M \rightarrow A + M \qquad (16)$$

where A^+ is an atomic or a molecular ion and M is a third body. These

recombinations (Reactions 12-16) are all electron temperature dependent and their coefficients are given in Table 1, taken from Reference 16.

TABLE 1

Recombination Rate Coefficients

T_e in (eV)

Reaction	Rate Coefficient
12	$4.3 \times 10^{-8}(T_e)^{-0.39}$ cm^3 sec^{-1}
13	$2.1 \times 10^{-8}(T_e)^{-0.63}$ cm^3 sec^{-1}
14	$\sim 10^{-12}$ at 300 $\overset{o}{K}$ cm^3 sec^{-1}
15	$5.2 \times 10^{-27}(T_e)^{-4.5}$ cm^6 sec^{-1}
16	$6.5 \times 10^{-31}(T_e)^{-2.5}$ cm^6 sec^{-1}

The critical electron density, N_e^c, for a plasma generated by radiation with a wavelength λ is

$$N_e^c = 10^{13} \lambda^{-2} \tag{17}$$

which implies that for microwave radiation with $\lambda > 1$ cm the critical electron density is $N_e^c \leqslant 10^{13}$ cm^{-8}. For such a condition and for a pressure of one atmosphere the recombination is, generally, dissociative (see Reactions 12 and 13) especially when electron temperatures are $\sim$ few eV. Thus for $T_e \simeq 1$ eV, $N_e = 10^{13}$ cm^{-3} the dissociative recombination rate is $4.30 \times 10^{-8} \times 10^{13}$ $\sim 4.3 \times 10^5$ sec^{-1} which is 15 times smaller than the attachment rate.

3.2 BREAKDOWN THRESHOLD POWER

The air breakdown calculation, in principle, can be carried out by solving Equation (5) and (6) with the knowledge of the electron velocity distribution and the appropriate atomic processes whose rates are electron energy dependent. However, reasonable estimates (lower limits) can be obtained for breakdown threshold power using approximate solutions. The rate of energy growth for the electron in the radiation field, Equation (3), can be written in terms of the incident radiation intensity, I, as

$$\frac{d\varepsilon}{dt} = \frac{4\pi e^2 I}{mc} \cdot \frac{\nu_m}{\omega^2 + \nu_m^2} = \frac{0.11\ I\ \nu_m}{\omega^2 + \nu_m^2} \qquad (18)$$

where $\frac{E^2}{4} = \frac{I}{c}$ was utilized ($E = 27\sqrt{I}$ (V/cm) with I in watts/cm^2. The threshold condition is obtained using Equation (18) assuming that energy gained by the electron is expended to ionizations and that other loss mechanisms are ignored. Thus the energy gained by the electron during the radiation pulse, Δt, is equal to the ionization potential of the atom or the molecule, I_i, times the critical number of generations, K_{cr},

$$\int_0^{\Delta t} \frac{d\varepsilon}{dt}\ dt = K_{cr}\ I_i \qquad (19)$$

Thus the threshold power for air breakdown is

$$I_{th} = \frac{I_i\ K_{cr}\ (\omega^2 + \nu_m^2)}{0.11\ \Delta t\ \nu_m} \qquad (20)$$

Some interesting observations can be made of the result in Equation 20. First, the threshold power for breakdown increases inversely with the radiation pulse width i.e. if one could generate a very short pulse then

one may transmit higher powers in air without breakdown. Second, for the microwave frequency $\omega^2 << \nu_m^2$, the threshold power increases as ν_m i.e. with pressure and is independent of the microwave frequency (high pressure regime).

For a pulsed breakdown the cascade electron density build up can be described by

$$N_e = N_e(0)\ e^{\nu \Delta t} = N_e(0)\ 2^{K_{cr}} \tag{21}$$

Where ν is the net ionization rate and $N_e(0)$ is the initial density of the free electrons, generally $\sim 1\ \text{cm}^{-3}$. Furthermore, it is assumed that at the end of the radiation pulse the electron density reaches its critical value, N_e^{cr} (see Equation 17), where

$$K_{cr} = 1.45 \log_e \left(\frac{N_e^{cr}}{N_e(0)} \right) \tag{22}$$

To estimate the threshold power for air breakdown under optical frequencies, Equation (20) can be utilized with K_{cr} values ranging[11] from 36 to 40. Using $K_{cr} = 40$ and $I_i = 14.8$ eV for the average ionization potential of air molecules in Equation (20) results in

$$I_{th} = 8.6 \times 10^{-16} \frac{\omega^2 + \nu_m^2}{\Delta t\ \nu_m} \ (\text{watts/cm}^2) \tag{23}$$

The collision frequency can be estimated[17] to be $\nu_m = 5.3 \times 10^9$ p where p is the air pressure in Torrs, therefore, Equation (23) reduces to

$$I_{th} = \frac{8.6 \times 10^{-16}}{\Delta t} \ \frac{\omega^2 + (5.3 \times 10^9\ p)^2}{5.3 \times 10^9\ p} \tag{24}$$

For optical region $\omega \simeq 10^{16}$ which is much larger than ν_m, one obtains for air at atmospheric pressure a breakdown threshold power of 2×10^{10} (watts/cm^2) using a pulse with duration of 10^{-6} sec. This value is of the same order but

lower by a factor of three compared to the breakdown threshold power obtained experimentally,[18] indicating that the classical approach can explain the breakdown process. Thus the breakdown calculations require the interrelation of many factors which are the ionization rate, the energy loss rate, the average electron energy, the electric field and finally, the threshold power for breakdown. This requires a more detailed analysis which is carried out in the next section for microwave breakdown of air.

3.3 AN ANALYTIC METHOD FOR THRESHOLD POWER CALCULATION

Various approaches to air breakdown calculations exist.[4-7, 18-20] Some start with the knowledge of the ionization rate of air, ν_i, which generally is expressed as $\frac{\nu_i}{p}$. This quantity depends on the electron energy which in turn depends on the critical electric field, $\frac{E_e}{p}$. For a Maxwellian electron velocity distribution and for an average electron energy of $\bar{\varepsilon} < 20$ eV, the following relation for $\frac{\nu_i}{p}$ has been obtained[20]

$$\frac{\nu_i}{p} = 2.5 \times 10^7 \left[5.6\ (\bar{\varepsilon})^{1/2} + 0.6\ (\bar{\varepsilon})^{3/2}\right] \mathrm{Exp}\left(\frac{18.75}{\bar{\varepsilon}}\right) \qquad (25)$$

where it is assumed that in air ionization is basically from oxygen molecule ($I_i \simeq 12.06$ eV). Furthermore, an empirical relation[20] has also been found between $\bar{\varepsilon}$ and $\frac{E_e}{p}$ where

$$\bar{\varepsilon} \simeq 0.0675\ \frac{E_e}{p} \qquad (26)$$

This relation utilized into (25) yields

$$\frac{\nu_i}{p} = 2.5 \times 10^7 \left[1.45 \left(\frac{E_e}{p}\right)^{1/2} + 0.01 \left(\frac{E_e}{p}\right)^{3/2}\right] \mathrm{Exp}\left(\frac{-278}{\frac{E_e}{p}}\right) \qquad (27)$$

which is shown in Figure 1. Thus the problem is a simple one for air breakdown when it is attachment controlled. For cw the condition for breakdown is

$$\nu_i = \nu_a \tag{28}$$

or equivalently

$$\frac{\nu_i}{p} = \frac{\nu_a}{p} \tag{29}$$

The value of $\frac{\nu_a}{p}$ is known and thus one can obtain $\frac{E_e}{p}$ from Equation (27). However, for pulsed breakdown, the ionization rate must be high enough so that the electron density reaches its critical value within the duration of the radiation pulse. This requires that

$$\frac{\nu_i}{p} - \frac{\nu_a}{p} = \frac{1}{p\Delta t} \log_e \frac{N_e^{cr}}{N_e(0)} \tag{30}$$

or

$$\frac{\nu_i}{p} - \frac{\nu_a}{p} = \frac{1}{p\Delta t} \log_e \left[10^{13}/\lambda^2 \cdot N_e(0)\right] \tag{31}$$

Thus for any wavelength, Δt and p we can obtain $\frac{\nu_i}{p}$. From Figure 1 or Equation (27) we obtain the corresponding $\frac{E_e}{p}$ and hence the threshold breakdown power. Using $\lambda = 3$ cm, $p = 760$ mm, $\Delta t = 10^{-6}$ and $N_e(0) = 1$ in Equation (31) we obtain $\frac{E_e}{p} \simeq 30$ volts/cm Torr.

An application of Equation (31) with $N_e(0) = 1$ for a fixed pulse duration ($\Delta t = 10^{-6}$ sec) is shown in Figure 2 for several different wavelengths. In this Figure $\frac{\nu_i}{p}$'s are given as a function of air pressure (altitude). The corresponding effective electric fields as a function of pressure (altitude) are shown in Figure 3. In this figure the independence of the electric field on the radiation wavelength with increasing pressure, is a manifest of the attachment controlled domain for breakdown.

3.4 AIR BREAKDOWN CALCULATION WITH DIFFUSION

The calculation in Section 3.2 was carried out ignoring the diffusion effect. However, when the density of air is reduced, diffusion may become an important factor in air breakdown and, therefore, it has to be considered. In this section we present air breakdown calculations by including the diffusion effects phenomenologically. In addition, we present the effect of the radiation pulse width on the breakdown thresholds.

The criterion for a cw breakdown is

$$\frac{\nu_i}{P} = \frac{\nu_a}{P} + \frac{D}{P\Lambda^2} \tag{32}$$

For a pulsed condition, however, the criterion for breakdown is

$$\frac{1}{P}\left(\nu_i - \nu_a - \frac{D}{\Lambda^2}\right) = \frac{1}{P\Delta t} \log_e \left(N_e^{cr}/N_e(0)\right) \tag{33}$$

This implies that two other parameters have to be known in order to calculate the critical field. These are, D and Λ. The diffusion coefficient is related to E_e/P according to

$$D\ P = \left[29.0 + 0.9\ \frac{E_e}{P}\right] \times 10^4 \tag{34}$$

and Λ is generally a characteristic length of the breakdown geometry and can be estimated. In Figure 4 we present breakdown threshold power calculations as a function of pressure for several wavelengths of the incident radiation. These calculations were carried out with $\Lambda = 0.75$ cm and $\Delta t = 3 \times 10^{-6}$ sec. It is obvious from this Figure that the threshold breakdown power increases with increased frequency of the incident radiation. However, these calculations were repeated for a shorter pulse width i.e. $\Delta t = 3 \times 10^{-7}$ sec. to demonstrate the effect of shorter pulse duration. These latter results are shown in Figure 5 where it is obvious that the reduction in the radiation

pulse width, for each wavelength, results in higher breakdown threshold power.

4. SOME APPLICATIONS USING AN NRL CHEMISTRY CODE

The NRL Master Code,[21,22] an E and F regions chemistry code, was utilized for the ionospheric electron heating and increased ionization. The code is described in detail elsewhere.[21,22] However, a brief description of the code is in order.

The code solves a set of coupled rate equations which predicts the time histories of the following species:
N_2, $N_2(A)$, N_2^+, O_2, $O_2(a^1\Delta)$, $O_2(b^1\Sigma)$, O_2^+, $O_2^+(a^4\pi)$, NO, NO^+, N, $N(^2D)$, $N(^2P)$, N^+, $N^+(^1D)$, $N^+(^1S)$, O, $O(^1D)$, $O(^1S)$, O^+, $O^+(^2D)$, $O^+(^2P)$, n_e, T_e, T_v and T_a, where for the species the ground state is implied whenever no electronic state is indicated. The electron temperature T_e, the vibrational temperature of the nitrogen molecule, T_v, and the kinetic temperature of the heavy particles, T_a are also calculated.[20,21] The code can accept any ionization and heating source to disturb the ionosphere and it is purely a chemistry code and does not contain transport or hydrodynamic effects, however, it can be coupled with such a code for a complete description of the disturbed air phenomena. The code, furthermore, can calculate the emission from various excited states of the ionospheric species. It can be used to gain further insight into microwave deposition into the ionosphere.

We have selected an altitude of 250 Km to deposit microwave radiation with $\lambda \simeq 3$ cm and a pulse duration of $\Delta t = 10^{-2}$ sec. Three sets of incident power densities were used 1, 10 and 10^3 Watt/cm^2 and some selected results of these calculations are shown in Figures (6-8). At a power density of 1 Watt/cm^2 no change occurs in the ambient electron density (Fig. 6). The energy gained by the ambient electrons, however, is expended in inelastic collisions resulting in excitations of various electronic states. The time histories of two such states, $O(^1S)$ and $O(^1D)$ of the oxygen atom are shown

in Figures 7 and 8. They are metastable states with life times[23] of ~ 0.6 sec and 135 sec, respectively. They emit radiation at $\lambda = 5577$ Å and the 6300 Å, respectively, and are the well known auroral[24] green and red oxygen emissions.

When the incident power density is raised to 10 and 10^3 Watts/cm^2, however, the electron heating and multiplication occurs resulting in peak electron densities of $\sim 2 \times 10^5$ cm^{-3} and 8×10^6cm^{-7}, respectively. For these cases the enhanced $O(^1S)$ and $O(^1D)$ densities are shown in Figures 7 and 8 with peak densities at 10 Watts/cm^2 being 8.5×10^3 and 2×10^5 cm^{-3}, respectively. The respective values at 10^3 Watts/cm^7 are 1.5×10^5 cm^{-3} and 1.7×10^7 cm^{-3}.

4.1 THE MICROWAVE ABSORPTION COEFFICIENT

In the previous section some results of the energy deposition in the ionosphere were presented. It is of interest, however, to know the penetration depth or the attenuation coefficient for the microwave radiation in air or gaseous medium in general. This quantity is essential for various applications e.g., the propagation length and the size of a plasma which can be generated by a radiation of a given intensity and wavelength.

The process of radiation absorption by the free electrons is the inverse Bremsstrahlung with two components. These are due to the electron neutral and the electron ion collisions in the field of an electromagnetic radiation. The corresponding absorption coefficients are[18,25]

$$\alpha_n = 10^{-34}\, n_e\, N\, \lambda^2 \sqrt{T} \tag{35}$$

and

$$\alpha_p = 2 \times 10^{-23} \left(\frac{1}{T}\right)^{3/2} n_e\, N^+\, \lambda^2 \quad , \tag{36}$$

respectively. In Equations (35) and (36) T is the electron temperature in degrees Kelvin, N and N^+ are the neutral and the ion densities, respectively and are valid for regions of $h\nu \ll kT$. Furthermore, in Equation (35) the momentum transfer cross section is assumed to be $\sim 10^{-15}$ cm^2. It is clear from these relations that when the degree of ionization is low, the dominant absorption mechanism is the inverse neutral Bremsstrahlung and when the degree of ionization rises the electron ion component becomes important and in many cases will predominate, especially when the breakdown is due to optical frequencies i.e. (lasers).

From these relations, it is obvious, that for our applications of microwave radiation at 250 Km with electron density of $(10^5 - 10^7)$ cm^{-3} and neutral density $\sim 10^9$ cm^{-3}, the absorption length is very long as if the radiation will never be attenuated. Therefore, one can generate a column of excited states many, many kilometers in length which will emit the green and the red oxygen lines. As an example the peak emissions of ^1S and ^1D for an incident microwave power of 1000 Watt/cm^2 are 2.5×10^5 and 1.2×10^5 photons per cm^3, respectively. For a column of 1 Km the emission from the green and the red lines will be 300 kR and 144 kR, respectively.

4.2 IONOSPHERIC MODIFICATION AND ITS IMPACT ON COMMUNICATION

In the previous section we gave estimates of the microwave power needed to increase the ionization level in the ionosphere. An obvious impact of the increased electron density would be the disruption of communications, at higher frequencies, between satellites and the earth. The disruption occurs when the ionosphere acts as a mirror for the transmitted frequency. This frequency is related to the critical electron density by Equation (17). More detailed studies on this area will be forthcoming.

5. AIR BREAKDOWN SPECTRA

The air at the sea level is a mixture of $N_2(2.1 \times 10^{19} cm^{-3})$ and $O_2(5.38 \times 10^{18} cm^{-3})$ i.e. with a ratio of 4 to 1. The molecular densities fall off exponentially with increasing height.[26] There occurs, however, a break from the exponential fall off for O_2 around 100 km, where the dissociation of O_2 becomes important, giving rise to the oxygen atom which becomes one of the dominant species at higher altitudes. For example, at 250 km the N_2 and O densities are $2 \times 10^8 cm^{-3}$ and $7.6 \times 10^8 cm^{-3}$, respectively.[26]

The air breakdown spectra will be due to band and line emissions from N_2, N_2^+, O_2, O_2^+, O, O^+, N and N^+ and various other species which are generated as a result of the breakdown. To this one must add plasma emissions due to various processes such as free-free free-bound, -bound-bound, etc. A detailed discussion on air breakdown emissions will be the subject of another report.

For air breakdown with microwave radiation at the sea level, however, under a single pulse (10^{-9} - 10^{-6}sec) operation, one may observe the emission spectra of N_2 and N_2^+, especially from the second positive bands of N_2 and the first negative bands of N_2^+. These two band systems correspond[27] to $N_2^+(B^2\Sigma \rightarrow X^2\Sigma)$ and $N_2(C^3\pi_u - B^3\pi_g)$ transitions, respectively. The emission in the second positive bands system extends from 2800 - 5000 Å with its (0,0) transition, at 3371 Å, being the strongest. The emission in the first negative bands system, on the other hand, extend from 3300 - 5900 Å with its (0,0) transition, at 3914 Å, being the strongest. In Table II some strong bands of these systems are presented along with their radiative transition rates.[28]

TABLE II

Strong Optical Transitions From N_2 Second Positive and N_2^+ First Negative Bands Systems

	Transition (v',v'')	Wavelength (Å)	Transition Rate (sec^{-1})
N_2	(0,0)	3371	1.11(7)*
	(0,1)	3576	7.27(6)
	(0,2)	3805	2.83(6)
	(1,0)	3159	1.02(7)
	(1,2)	3536	4.7(6)
	(1,3)	3755	3.93(6)
	(1,4)	3998	1.24(7)
N_2^+	(0,0)	3914	1.24(7)
	(0,1)	4278	2.2(6)
	(1,2)	4236	2.66(6)
	(1,3)	4651	1.93(6)

(*) 1.11(7) read 1.11×10^7

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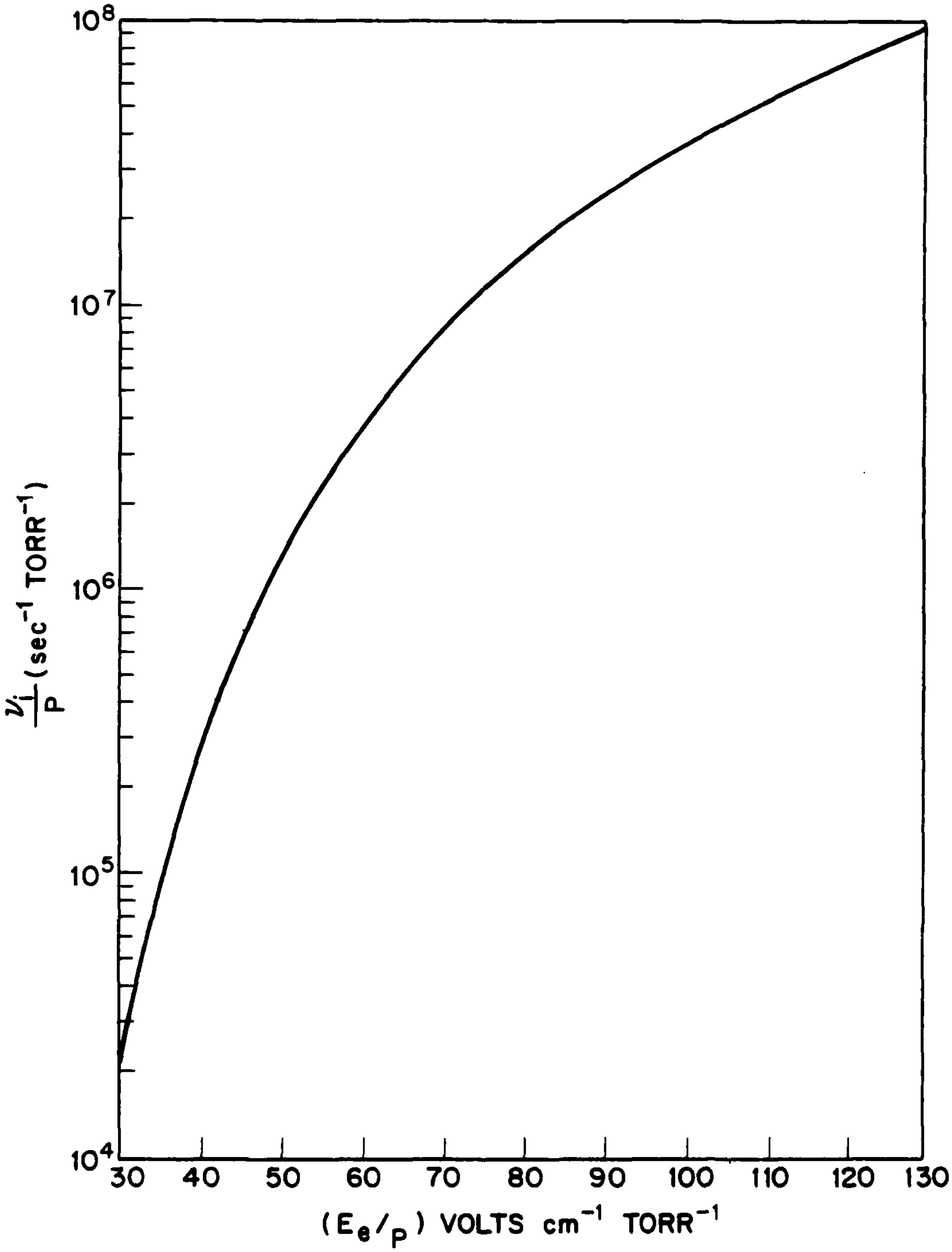

Fig. 1 — The ionization frequency per Torr ν_i/p as a function of E_e/p

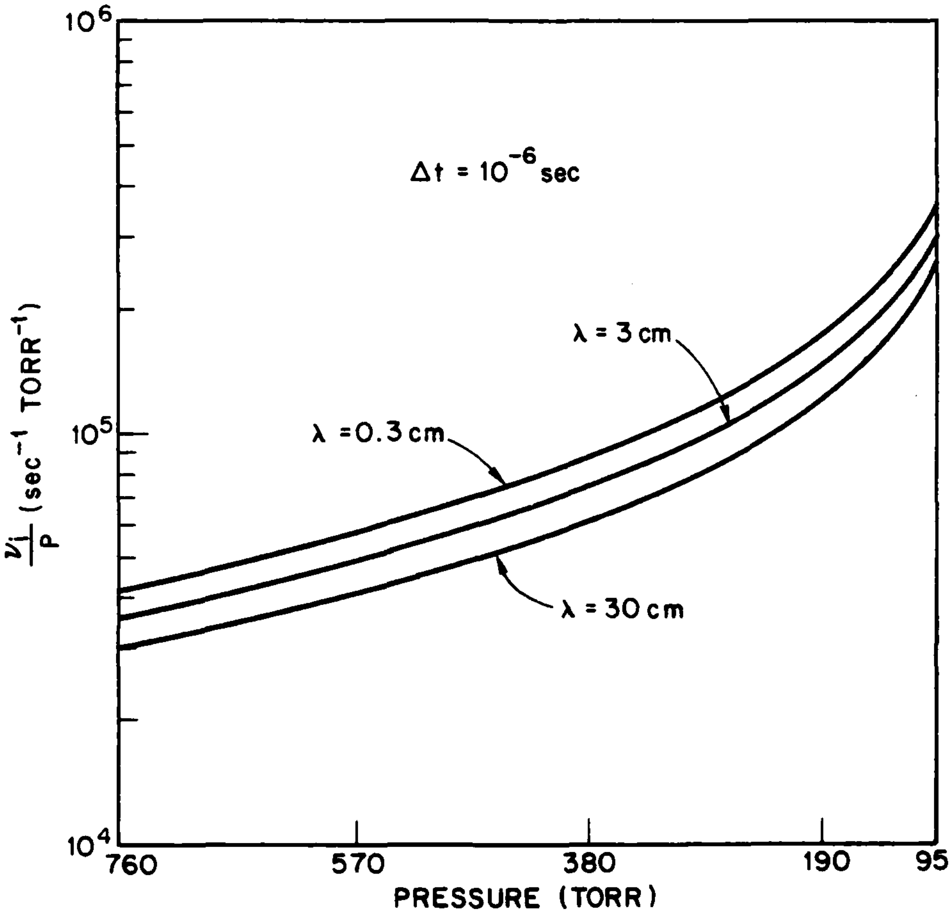

Fig. 2 — The ionization frequency per Torr as a function of pressure for several incident radiation wavelength with $\Delta t = 10^{-6}$ sec

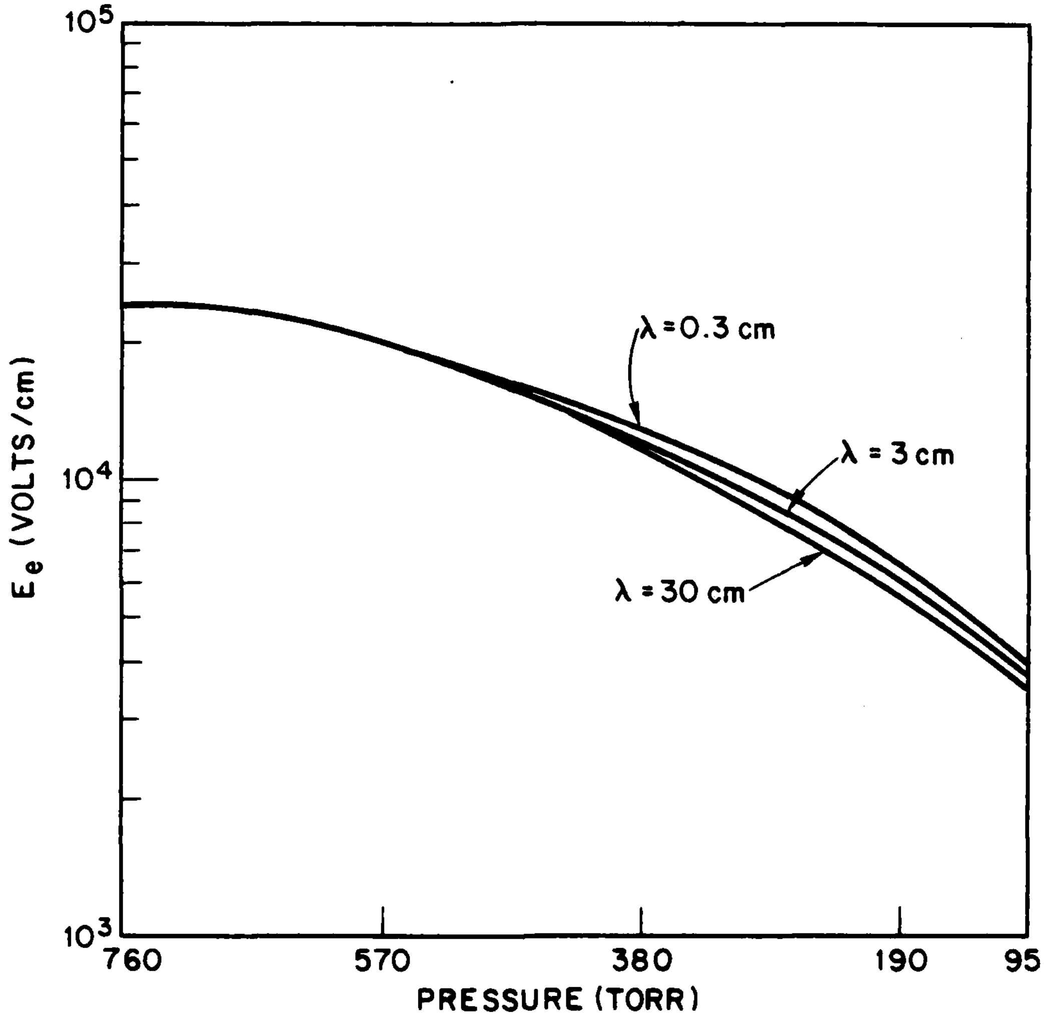

Fig. 3 — The corresponding effective electric field for Fig. 2 as a function of pressure

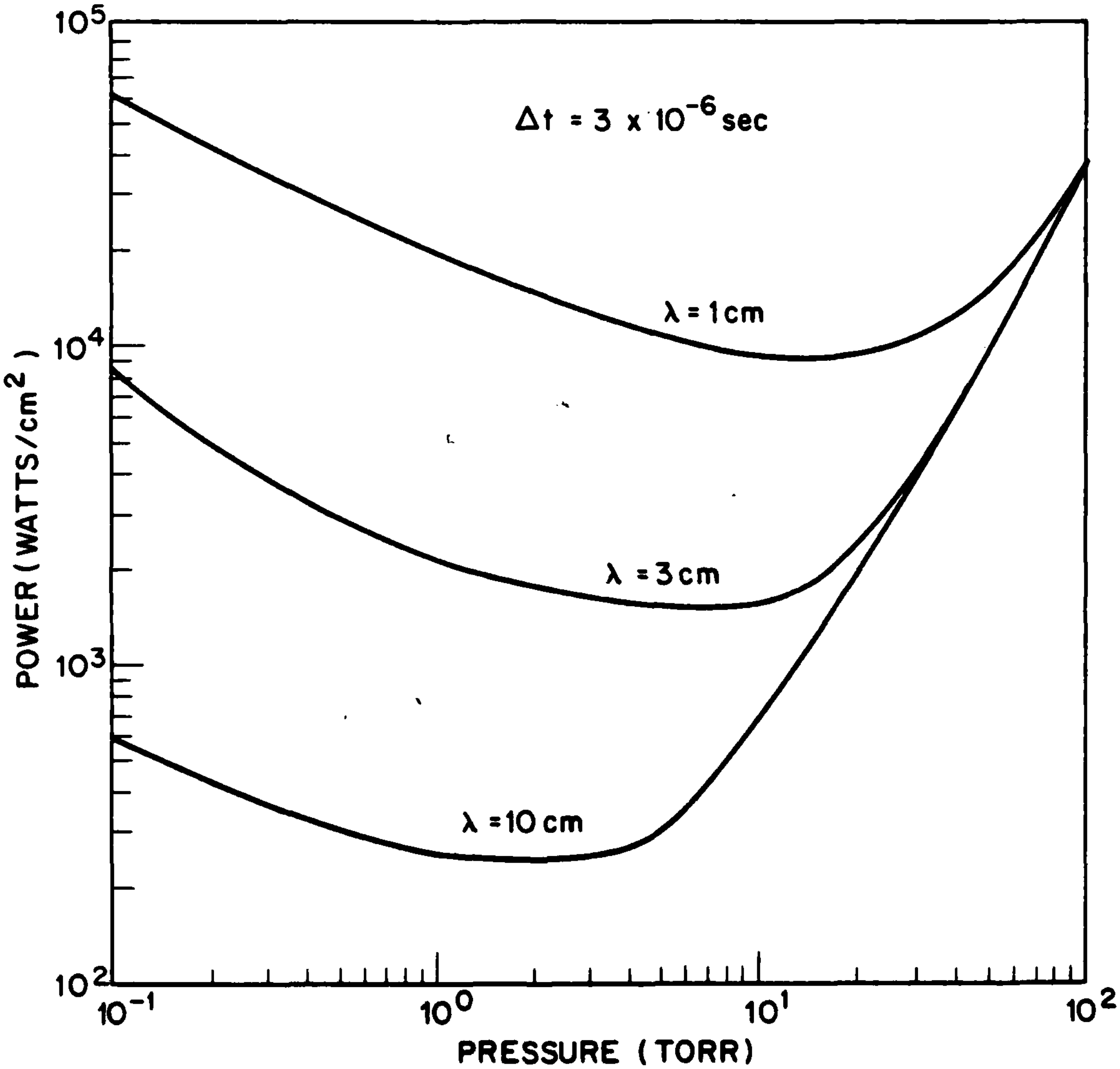

Fig. 4 — Threshold power for air breakdown as a function of pressure for various wavelengths and a radiation pulse width of 3×10^{-6} sec

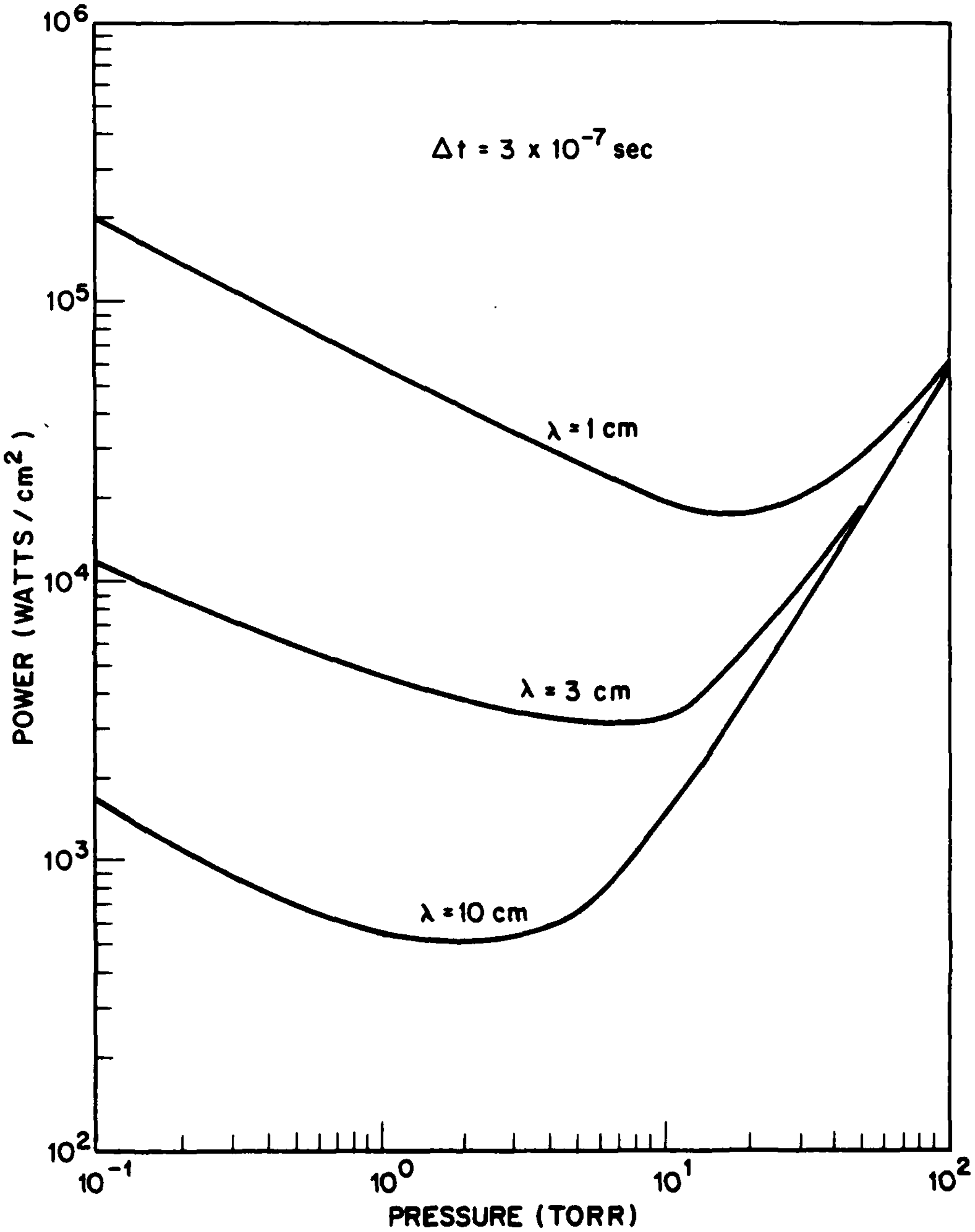

Fig. 5 — Same calculation as in Fig. 4 for a shorter radiation pulse width (3×10^{-7} sec)

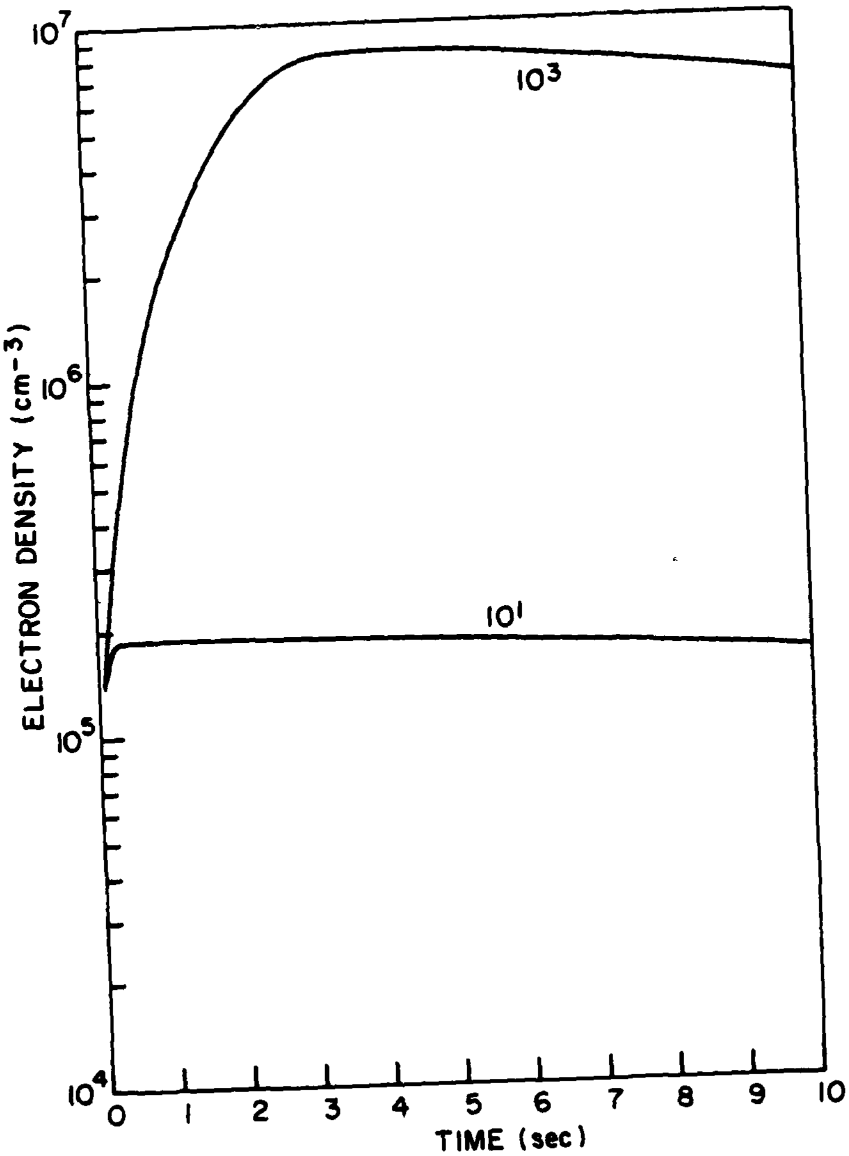

Fig. 6 — The electron density as a function of time for an altitude of 150 Km irradiated by microwave radiation pulse of 10^{-2} sec at 10 and 10^3 Watts/cm^2. (The ambient N_e was assumed 10^5 cm^{-3}.)

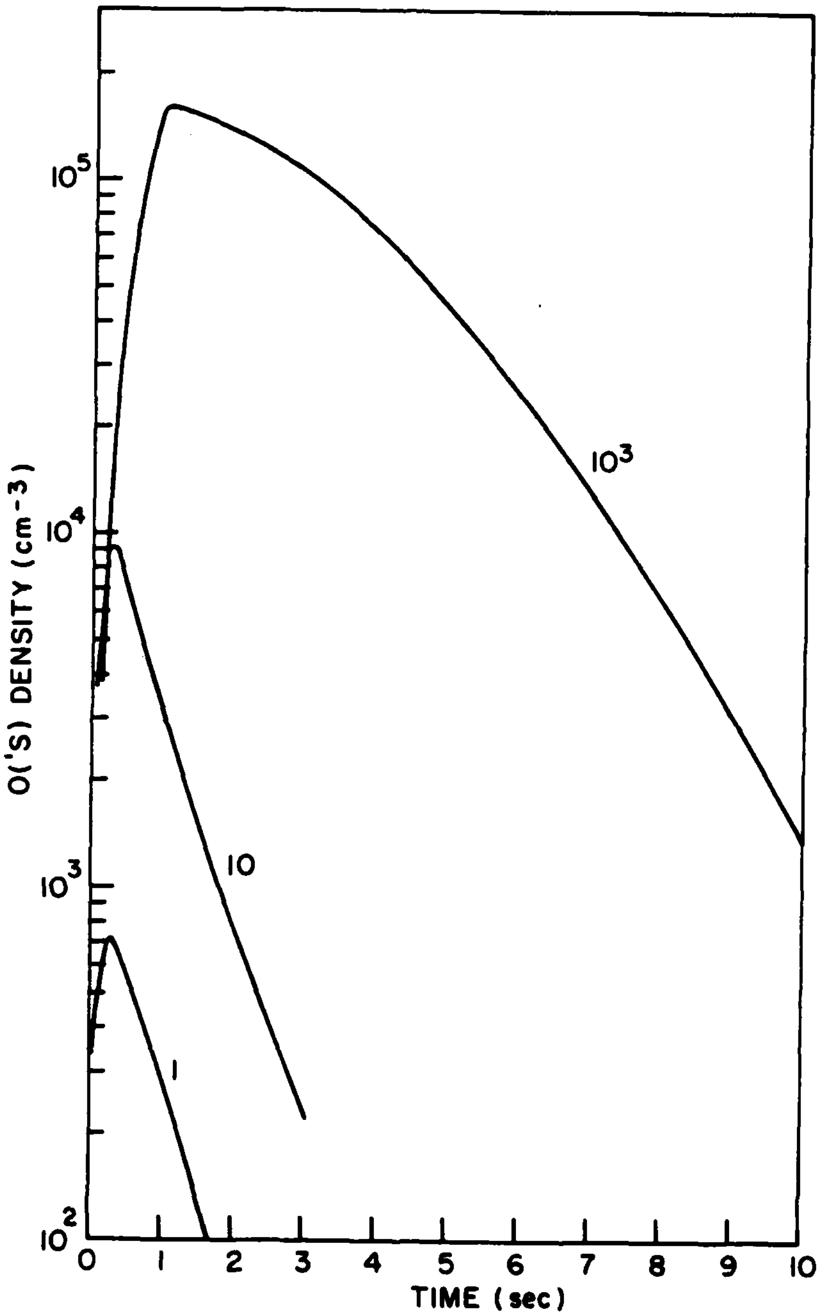

Fig. 7 — The time history of O(^{1}S), which emits the green line at 5577 Å, at an altitude of 250 Km for microwave radiation power densities of 1, 10 and 1000 Watt/cm^2. The radiation pulse width is 10^{-2} sec.

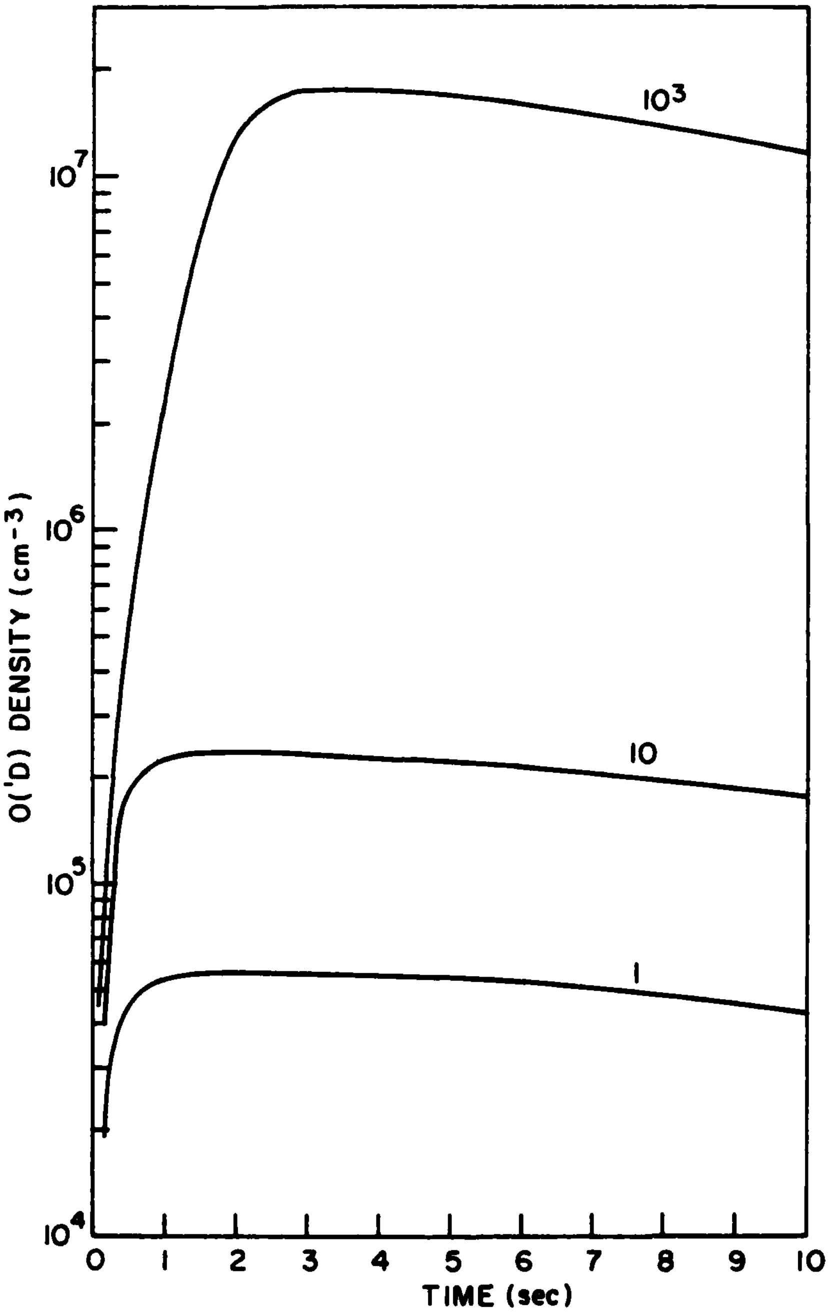

Fig. 8 — The time history of $O(^1D)$, which emits the oxygen red line, at 6300 Å, at an altitude of 250 Km for microwave radiation power densities of 1, 10 and 1000 Watts/cm^2. The radiation pulse width is 10^{-2}sec.

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